Correlation of Glottal Area Function Within Three Registers as Revealed Through Measurement of Ultra-High-Speed Photographs and Photo-Electric Glottographs

By

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Abstract of Dissertation Presented to the Graduate Council
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CORRELATION OF GLOTTAL AREA FUNCTION WITHIN THREE REGISTERS AS REVEALED THROUGH MEASUREMENT OF ULTRA-HIGH-SPEED PHOTOGRAPHS AND PHOTO-ELECTRIC GLOTTOGRAPHS

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Chairman: Dr. G. Paul Moore
Major Department: Speech

Based on the hypothesis that measurement of the quantity of light passing through the glottal area should reveal the same information derived from measurement of the discernible space between the vocal folds, the major purpose of this investigation was to determine the validity of the photo-electric glottograph as a measuring device as compared with a frame-by-frame analysis of ultra-high-speed photographic film. A second purpose was to describe and compare the characteristic glottal configurations in falsetto, modal, and vocal fry registration of pre-adolescent, adolescent, post-adolescent, and adult subjects as revealed by the two methods of investigation. To achieve these purposes, simultaneous recordings of the visual image of the vocal folds, the voice signal and the deviations sensed by the phototransducer during falsetto, vocal fry, and modal

phonation were obtained from five subjects. These subjects had met the following criteria: (1) they showed no evidence or history of voice disorders or laryngeal pathology; (2) they were capable of complete anterior-posterior exposure of the vocal folds; (3) they were capable of phonating in vocal fry, modal, and falsetto registers; and (4) they presented five types of laryngeal development (pre-adolescent, adolescent, post-adolescent, adult male and adult female).

Recordings were made during sustained phonation of the vowel /i/ for each of the registers investigated. Intra-oral voice recordings made during photography were subjected to a fundamental frequency and intensity analysis.

Measurements of glottal area function were made on six consecutive cycles from the steady-state portion of each film. Glottal area was determined in the laryngeal photographs by standard polar planimeter methods. The amplitude and frequency deviations produced by the oscillographic trace of the phototransducer were measured from the trace representing the 5k Hz signal. Correlation between the normalized curves produced by the two methods was determined and confidence intervals established.

The results indicated that the photo-electric glottograph represents glottal area function as revealed in high-speed photography. In addition, the use of the glottographic

method of investigation in conjunction with photographic procedures may lead to more complete understanding of the phase relationship between the upper and lower margins of the folds. The vibratory patterns exhibited by two subjects during the production of falsetto register suggest the participation of myoelastic factors.

CHAPTER I

INTRODUCTION AND STATEMENT OF THE PROBLEM

Introduction

The nature of vocal fold vibration has in the past been the subject of wide differences of opinion (Musehold, 1897; West, 1926; Metzger, 1928; Tarnoczy, 1951). Presently, it is accepted that the vocal folds vibrate synchronously at a frequency that determines the fundamental pitch of the tone being produced, alternately allowing momentary outflow and stoppage of the air stream which is forced up from the lungs below by the muscles of exhalation (Moore, 1937b; van den Berg, 1958, 1960). The quality of the sound produced by the speaker is dependent on the manner in which the vocal folds vibrate.

Researchers have employed various methods for observation of the activity of the laryngeal mechanism over the past 186 years. Moore (1937a) presented an historical accounting of methods used in vocal fold research. Black (1951), Luchsinger and Arnold (1965), and Peterson (1958) have outlined the procedures used in current investigations.

With the advent of the laryngeal mirror, stroboscopic techniques, radiographic procedures, spectroscopic analysis, normal- and ultra-high-speed photography, and glottography, much is now known of the normal vibratory patterns in the different frequency ranges of the human voice.

Ultra-high-speed photography has afforded a reliable method for study of the complex vibratory movements of the vocal folds in the normal larynx (Farnsworth, 1940; Moore et al., 1962). Moore (1937b) reported that the opening of the glottis begins anterior to the mid-point of the folds and progresses in a posterior direction. This information contradicted conclusions derived earlier from stroboscopic photography on the nature of vibratory closure. Brackett's (1947) analysis of high-speed photographs of the vibrations of the vocal folds of two male subjects revealed differences in the proportion of time occupied by each of three phases of the vibratory cycle, closed, opening, and closing. Not only were these differences noted between subjects but also for different performances by the same subject. These results were confirmed by Smith (1954). The expected time ratio of three phases was postulated by van den Berg (1968a) who stated that the glottis should remain closed for two-thirds of each period for low tones; whereas the closing time should decrease with rising pitch. This conclusion led to a definition of the opening quotient of the glottis as representing the time occupied by each opening in relation to the total time of each period. Thus, low tones show a small opening quotient and high tones show an increasing opening quotient up to 1.0 when the glottis remains open throughout the cycle for falsetto tones. Information on vibratory patterns associated with different types of phonation is now available (Arnold, 1957; Moore, 1968a; van den Berg, 1958, 1960; Vennard, 1960). The phase relationship of the upper and lower margins of the vocal folds has aided in the physiological description of register phenomena (Miller, 1959).

Although the meaning of the term "voice registers" appears to have no completely acceptable definition (Morner _et al_., 1963), there appear to be distinctive acoustic, physiological, and perceptual attributes characteristic for each of three ranges found in the normal production of voice (van den Berg, 1968b). Hollien and Michel (1968) included in their definition of "register" these criteria: (1) each shall be composed of a series of consecutive fundamental frequencies of a similar quality and (2) there should be little or no overlap of frequencies between registers. It was also found that subjective agreement between judges could be made for register change. More recently, Hollien (1971) has proposed three new terms in the definition of three major vocal registers. Synonymous with vocal fry, pulse register occupies the lowest range of frequencies within the individual phonation range. Modal register designates that range of frequencies correlated with normal, chest and head, or low, mid, and high. This register is composed of those fundamental frequencies that are normally used in speaking and singing. Loft register is that register ordinarily designated as falsetto. This register includes the higher fundamental frequencies within an individual vocal range. For the purposes of this investigation, it seems appropriate to rely upon two of the more traditional terms, consequently, the registers will be designated as vocal fry, modal, and falsetto.

The study of vocal registration has been directed not only to the phonation of the adult but also to that of the child in an effort to define and compare various register productions appropriate for the vocal mechanism in changing stages of maturation. Investigators have established criteria for three vocal registers in the adult for both sexes (Luchsinger and Arnold, 1965; Pronovost, 1942; Snedicor, 1951; Colton, 1969; Hollien and Moore, 1960; Hollien and Michel, 1968; Hollien et al., 1971). Sedláčková (1961) found that the phonation ranges of children demonstrated the presence of three registers. Her findings were obtained by means of stroboscopic motion pictures. The appearance of the vocal folds was found to be like that of the adult mechanism within the production of chest, mid, and head register. Luchsinger and Arnold (1965) and van Oordt and Drost (1963) have also defined the frequency range and register production of the voice in children. They found that falsetto and modal registers may be qualitatively differentiated.

Motion picture studies (Fletcher, 1958) and radiographic procedures (Russell, 1931) have resulted in understanding of the physiologic changes manifested by the vocal folds within three registers. Vocal fry, described as a succession of laryngeal vibrations of low frequency (Hollien et al., 1966), has been the subject of radiographic investigations. The vocal folds appear to be compact and shorter in length in production of this particular register (Hollien et al., 1969). The results obtained from motion picture studies indicate that the vibratory cycle may be monophasic or biphasic. Further, the initial excursion of the folds presenting a biphasic pattern appears to be 25 percent smaller in amplitude than does the second. Apparently the plateaus noted in the open phase are related to the longitudinal opening waves which travel along the length of the vocal folds (Moore and von Leden, 1958; Timcke et al., 1959).

The modal register has been equated with the natural range, and chest or mid register (van den Berg, 1960). Fink and Kirschner (1959) observed that the configuration of the vocal and ventricular folds should be smoothly curved and symmetrical in production of modal register. They also indicated that the medial surface of the folds should be convex during phonation. This observation was confirmed by Sovak et al. (1971). Laminagraphic studies of the vocal folds revealed that as the fundamental frequency of phonation is raised the vocal folds tend to elevate progressively. The angle of tilt also appears to increase as pitch elevates except in production of frequencies within the falsetto register (Hollien and Curtis, 1962).

Normal speed photography reveals that in the modal register there is systematic lengthening of the vocal folds as frequency of phonation elevates (Hollien and Moore, 1960; Hollien, 1962). In addition, this lengthening may proceed in a stair step fashion. Ultra-high-speed motion pictures (Timcke et al., 1958) revealed that the opening quotient and speed quotient are similar in head and chest register. Increases in intensity appear to effect a faster opening quotient whereas the open quotient is inversely proportional to the intensity of the sound. Pitch changes do not appear to effect a change in either speed quotients or open quotients.

Moore (1968a) has cautioned that the initial vibratory movements of the vocal folds are usually extremely small and may be limited to only a portion of the glottal margin. Further, a medial motion may commence in a lateral direction. Vibration of the folds may appear with an open glottis when the diameter is not exceedingly large (van den Berg et al., 1957).

Subjective perceptual agreement is possible in judging production of the falsetto range (Rubin and Hirt, 1960; Hollien and Michel, 1968). Physiologically, the margins of the vocal folds have been found to be rather thin and pointed with vibration confined to this area (van den Berg, 1958). Rubin and Hirt (1960) described three patterns of vibratory activity for falsetto production. These were classified as open chink, closed chink, and damping. Furthermore, they found that as the untrained singer progressed through the phonatory range to the falsetto, this production elicited turbulent, chaotic vocal fold activity. It was concluded that aerodynamic forces contributed more to production of the falsetto than did myoelastic properties. This conclusion was verified by Hollien et al. (1971).

Motion picture studies and radiographic techniques (Griesman, 1943) have been successful in clarifying some aspects of larnygeal function. Unfortunately, due to the mechanics of these methods, physiological studies have been limited to the investigation of sustained vowel sounds or to non-speech activities. Further limitations are imposed not only by the cumbersome aspect of the equipment but also by the necessity for great subject cooperation. Camera techniques necessitate the use of subjects who are able to tolerate a laryngeal mirror in the pharynx and who are capable of full anterior-posterior exposure of the vocal folds.

Two relatively new techniques are being employed in the investigation of laryngeal activity during connected speech. The use of a fiber optics system for photographic investigation is still in its infancy. Investigators (Sawashima and Hirose, 1968; Sawashima et al., 1969) have devised a fiber optics cable that may be inserted through the nasal passages. A 16 mm camera is attached to the eyepiece of the image guide with illumination provided by a 150 watt incandescent lamp. Motion pictures with a frame rate of 24 per second are thus possible. Unfortunately, there is the distinct probability of subject discomfort. The fiber optics cable placed in the nasal passage presents a diameter of approximately 6 mm. In addition, the illumination provided by the light source is not sufficient for ultra-high-speed exposure.

During the last 55 years, considerable interest has been directed to a new method for recording the movements of the larynx (Spencer, 1917). The method has been termed glottography or laryngography. Researchers have proposed that through use of this procedure, direct examination of vocal fold movement in connected speech without undue subject discomfort is possible.

Hartmann and Wullstein (1938) were the first investigators to make any extensive use of a photo-electric cell for sensing vibrations of the vocal folds. They associated the results of the glottogram with those of the phonogram using a double beam oscilloscope. The waves produced by the glottogram resembled a series of positive sinusoidal waves with the exception that the opening phase appeared to be more gradual than did the closing phase. More recently, improvements have been made on this photo-electric glottographic technique (Sonesson, 1959; Ohala, 1966, 1967; Coleman and Wendahl, 1968; Sawashima, 1969; Lisker et al., 1969; Lindqvist, 1969; Frokjaer-Jensen, 1970).

Fabre (1957) and Decroix and Dujardin (1958) used an electronic process based on the principle of a high frequency current modulated by a low frequency current. The movements of the larynx of the subject, placed in an impedance bridge, were thus recorded in the shape of electrical variations. The primary objection to this method of analysis proved to be electrode placement and size. Fourcin and Abberton (1971) have modified the electrodes and their placement in their Laryngograph. The circuitry of this device is postulated to allow for self compensation for speaker impedance variation and is responsive only to fast changes resulting from vibration of the vocal folds in ordinary phonation rather than gross laryngeal displacement.

An ultrasonographic method for studying the vibratory movements of the vocal folds has been developed by Minifie et al. (1967). Hertz et al. (1970) found that the ultrasonic glottograms presented the same appearances as that obtained with the photo-glottographic method. The technique makes use of short ultrasound-pulses delivered to the surface of the neck. As echoes are received from the vocal folds, ultrasonograms are developed depicting the vibratory amplitude of the vocal folds. Although the gross appearance of movement has been found to be similar to that produced by the photo-glottographic method, the authors suggest that refinement of the equipment is still indicated before exactness of vibratory patterns can be expected.

Lindqvist (1970) used an inverse filtering technique to obtain glottograms of vocal fold activity. Volume velocity waveforms were used to derive information.

Calculations of the opening, closing, and closed phases were made.

Investigators have made comparison between results derived from one type of glottograph to another type, and found that, while there is similarity of wave form configuration, there is no one-to-one relationship (Fant et al., 1967; Köster and Smith, 1970; Frokjaer-Jensen, 1970). Apparently, some variation of results may be due to registration change as well as subject subcutanous fat deposit differences in the throat area.

Phonograms and glottograms have been compared in an attempt to relate glottal area function to results depicted by the data derived from these methods (Fabre and Frei, 1959; Van Michel, 1966; Dolansky and Tjernlund, 1967; Vallancien and Faulhaber, 1967; Lebrun and Hasquin-Deleval, 1971). Great differences in wave form have been noted. It has been concluded that some of the differences may result from the peculiar ability of the vocal folds to vibrate without producing voice.

Photography has proved to be a reliable and valid means for obtaining information of glottal area function; therefore, it would appear reasonable to make comparison of wave forms derived by frame-by-frame analysis to those resulting from the use of glottographic techniques (Zemlin, 1959). Sonesson (1960) was one of the first investigators to make such a comparison. The comparison was made between glottograph wave forms and wave forms developed through measurement of the distance between the medial margins of the vocal folds. The results indicated that the open quotient developed through these methods was identical. He suggested that the phase difference between the lower and upper edges of the vocal folds could be represented by the closed interval of the glottogram. This would seem to indicate that amplitude of the curve should be evaluated. Unfortunately, the curves derived were not obtained through simultaneous recording of glottographic and photographic procedures.

Great similarity of wave forms produced by the two techniques have been found by other investigators (Sawashima et al., 1968; Van Michel et al., 1970; Lindqvist and Lubker, 1970). Unfortunately, the method of measurement remains unknown.

Two investigations made by Wendahl and Coleman (1967, 1968) provoke some question of the validity of the information derived through glottographs. Their frame-by-frame analysis of glottal function derived by polar planimeter measurement produced information on the total area. These data were then compared to the curves simultaneously developed with the glottograph. The dissimilarity of the wave forms places the validity of the glottographic technique in some jeopardy. The measurements of glottal width rather than glottal area may be one factor influencing the disparity of fit noted in their glottogram data. Another factor that should be considered is the degree of vocal fold exposure. The subjects who participated in the study may not have attained the same degree of glottal area exposure.

Statement of the Problem

Previous studies of glottal area function have made use of methods that have either been established as capable of deriving valid physiological data or investigators have made assumptions of glottal activity based on data derived from equipment ordinarily utilized in acoustical investigations. To date, measurement procedures employed in the study of the vocal mechanism have not been specifically described and replicated in subsequent investigations. Further, adequate identification of the frequency, intensity, and register of the phonational sample has not been consistent.

Based on the hypothesis that measurement of the quantity of light passing through the glottal area reveals the same information derived from measurement of the discernible space between the vocal folds, the major purpose of this study was to determine whether the method of photoelectric glottography is as valid for depicting glottal area function as a frame-by-frame analysis of ultra-high-speed film. A second purpose was to describe and compare the characteristic glottal configurations in falsetto, modal, and vocal fry registers of pre-adolescent, adolescent, post-adolescent, and adult subjects as revealed by the two methods of measuring glottal area function.

CHAPTER II

PROCEDURES

The plan of this study was to obtain simultaneous indications of glottal area function as photographed by means of ultra-high-speed camera equipment and as sensed by the phototransistor of a photo-electric glottograph during the production of falsetto, modal, and vocal fry phonation. Five individuals (1 pre-adolescent male, 1 adolescent male, 1 post-adolescent male, 1 adult male, and 1 adult female) who possessed no evidence or history of voice disorders or laryngeal pathology served as subjects. The photographs and glottograms were obtained during sustained phonation of the vowel /i/ which provides the most complete exposure of the anterior-posterior aspect of the vocal folds. The samples were produced at medium vocal effort for each of the registers. The vocal registration was determined by agreement between the subject and the investigator.

Equipment

A block diagram of the instrumentation employed in the present study is shown in Figure 1. The subject sat on an

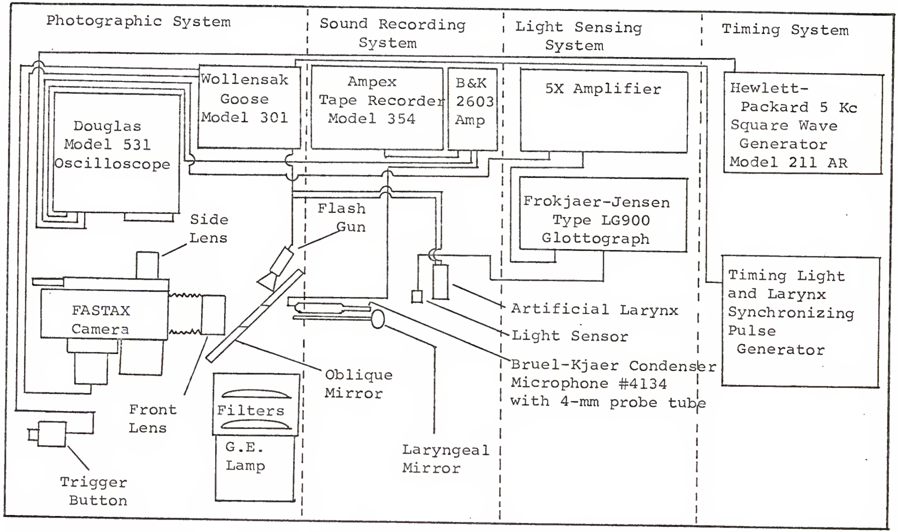
Photographic System
Sound Recording System
Light Sensing System
Timing System
Douglas Model 531 Oscilloscope
Wollensak Goose Model 301
Ampex Tape Recorder Model 354
B&K 2603 Amp
5X Amplifier
Hewlett-Packard 5 Kc Square Wave Generator Model 211 AR
Frokjaer-Jensen Type LG900 Glottograph
Timing Light and Larynx Synchronizing Pulse Generator
Side Lens
Flash Gun
FASTAX Camera
Artificial Larynx
Light Sensor
Bruel-Kjaer Condenser Microphone #4134 with 4-mm probe tube
Oblique Mirror
Front Lens
Filters
G.E. Lamp
Laryngeal Mirror
Trigger Button

Figure 1. Block diagram of equipment used to obtain the voice signals and simultaneous photographic and glottographic records of glottal area functions for each subject

adjustable stool before a fixed laryngeal mirror and introduced the mirror and the probe microphone into his pharynx. The phototransducer was affixed to the neck of the subject in the space between the anterior-inferior boundary of the thyroid cartilage and the anterior-superior boundary of the cricoid cartilage. The neck was then draped with black plastic material to block extraneous light sources and thus achieve maximum sensitivity of the transducer. Following amplification of the voice source by a condenser amplifier and of the glottal area function by the glottograph and external amplifier, each of the two signals were displayed on the face of an oscilloscope. As the subject achieved full exposure of the vocal folds for each register production, ultra-high-speed photographs were made of the vocal folds and of the product of the voice source and glottal area function as displayed on the face of the oscilloscope.

For monitoring phonation, the voice signal was recorded on an Ampex 354 full-track tape recorder. This signal was subsequently subjected to fundamental frequency analysis on an oscillographic writer and to intensity analysis by a graphic level recorder.

Instrumentation for obtaining ultra-high-speed photographs

Standard Fastax ultra-high-speed photographic procedures were used to obtain simultaneous photographs of the activity of the vocal folds and the photocell monitoring device recorded on one channel of an oscilloscope. This activity was filmed at an exposure rate of approximately 5000 frames per second.

Specifically, the photographic equipment consisted of a model WF 301 Wollensak Goose control unit set in position one to allow the event and the camera to start at the same time. The event is defined as the desired exposure of the laryngeal area. At the end of the time cycle, the event and the camera stopped. A timing impulse control unit made up of a time delay, electro-larynx drive, electro-larynx and a flash/sync generator were used to drive a Heathkit square wave generator thus producing a 5 kc square wave and flashing a time marker for the film. The 5 kc square wave was displayed on one channel of a Douglas 531 four channel oscilloscope.

The side lens of the Fastax camera was focused on the face of the oscilloscope, thereby photographing the wave form generated by the 5 kc square wave as well as those produced by the input of the photo-electric glottograph and the condenser microphone. The Fastax camera was fitted with an extension bellows and a 152 mm telephoto lens. The F stop was set at 3.5. The camera was loaded with Kodak 4 XR film #7277 with double perforations of 0.3000 inch pitch.

Illumination for filming and for glottography was provided by a 2100 watt, 60 volt General Electric projector lamp. Cooled light was directed by lenses and a mirror to a laryngeal mirror in the pharynx from which it was reflected into the larynx. The light that passed through the glottal opening between the vocal folds struck the anterior laryngeal wall subglottally and at the level of the phototransducer located on the external surface of the neck.

Instrumentation for obtaining phototransistor glottographs

Glottographs of glottal area function were obtained by a phototransducer mounted in a polyethylene tube with an internal diameter of 2 mm and an external diameter of 3 mm. The transducer was connected to a DC amplifier housed in a Frokjaer-Jensen Photo-electric Glottograph, type LG900, by means of a short shielded cable. This, in turn, was connected to a five times operational amplifier.

In total darkness, the phototransducer produces an input voltage to the amplifier of 0.7 μV. In position over a closed glottis the input voltage is 3.7 μV. A fully opened glottis yields an input voltage of 6 mV. The input level varies only up to 3 mV under conditions of normal phonation. Amplification of the glottography system is linear within plus or minus 2 percent in the normal working range of 0-3 mV input voltage. The power gain is 80 dB maximum. By means of a Philips Stroboscope type 9103, the frequency range of the glottograph was tested and found to be from DC-10,000 Hz. The signal from glottograph output A with a 4 volts/67 mA maximum in a 60 ohm load was input to a five times operational amplifier and thence to one channel of the Douglas 531 four channel oscilloscope. The output voltage selector was set at maximum.

In the present study, the phototransistor was affixed with adhesive tape to the neck of the subject at a point rostral to the superior boundary of the anterior aspect of the cricoid cartilage. The upper and lower length of the transistor was indicated by a line drawn on the neck of the subject. This procedure was used to afford a position monitor for the transistor at the beginning of each film sequence. The neck was then draped with black plastic material to exclude all extraneous light.

Measurement devices

To provide a base line response from the glottograph and a millimeter scale for glottal area measurement, a modification of the procedure developed by Hollien and Moore (1960) was employed. Immediately following the photographic procedure for each register and without any adjustment of the lens, a millimeter scale was photographed. This technique permitted measurement not only of vocal fold function but also served as a "no response" line for measuring glottograph response.

Experimental Procedure

Subjects

Five individuals were selected for the investigation. The subjects volunteered to perform the tasks and were chosen on the basis of the following criteria: (1) they showed no evidence or history of voice disorders or laryngeal pathology; (2) they were capable of complete anterior-posterior exposure of the vocal folds; (3) they were capable of phonating in vocal fry, modal, and falsetto registers; and (4) they presented five types of laryngeal development (pre-adolescent, adolescent, post-adolescent, adult male, and adult female).

Training Procedure

To provide an experimental environment for subject task practice, a training station was devised. This consisted of a fixed laryngeal mirror, a light source, and a subject viewing apparatus. The light source consisted of a high intensity lamp with the beam directed onto an ophthalmoscope mirror. The reflected light of the ophthalmoscope mirror was adjusted to illuminate the fixed laryngeal mirror. The subject viewing apparatus included a transparent mirror placed at a 45° angle which directed the image of the vocal folds to a mirror 20 inches above the base of the station.

This mirror was inclined at a variable angle, thus allowing the subject to monitor vocal fold activity and duplicating the experimental environment. The back of the station support box was equipped with a two-way mirror to permit viewing of the larynx of the subject by the investigator. A three-dimensional drawing of the station may be seen in Figure 2.

Tasks

After the investigator affixed the phototransducer for recording glottograph traces, the subject sat on an adjustable stool before a fixed laryngeal mirror and introduced the laryngeal mirror and probe microphone into his pharynx. Each subject was then instructed to produce a sample of the vowel /i/ in the register under investigation. The investigator observed the image of the subject's vocal folds in the viewing mechanism of the camera and checked the accuracy of the phonation range. The traces of the output of the microphone and the glottograph were observed for adequate illumination and placement on the face of the oscilloscope. When a full exposure of the vocal folds was visualized the investigator indicated that the subject should sustain the phonatory posture and the controls for the camera and the electrolarynx were triggered by the remote switch. Thus,

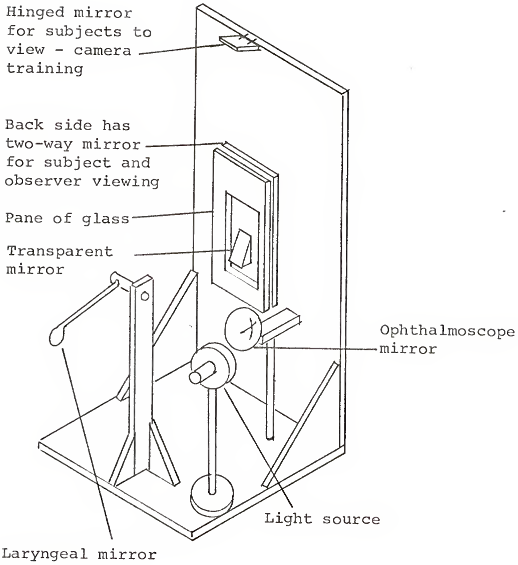
Hinged mirror for subjects to view - camera training
Back side has two-way mirror for subject and observer viewing
Pane of glass
Transparent mirror
Ophthalmoscope mirror
Light source
Laryngeal mirror

Figure 2. Three-dimensional drawing of subject training station

simultaneous indications of laryngeal activity as viewed through the camera, sensed by the phototransducer, and recorded by the microphone, were photographed in each of three registers. After each phonation was filmed, the millimeter grid was brought into focus and photographed as the subject viewed the adducted vocal folds with a hand-held laryngeal mirror. Appendix A contains the recording itinerary followed throughout.

Falsetto Range

Following the experimental tasks, verification of the production of falsetto register was confirmed for each subject. Four phoneticians and the investigator listened to the production of the complete vocal range of each subject. The experimental sample was then reproduced immediately after the vocal range was presented. Agreement between the judges was found to be unanimous for each sample. The judgment form is reproduced in Appendix B.

Data Analysis

Glottal area function was determined by traditional polar planimeter methods with total area of glottal opening in successive film frames plotted as a function of time. This necessitated measuring the activity of the vocal folds for each frame in a cycle three times and dividing by three to obtain a high degree of accuracy. The use of a Kodak Photo-Optical Data Analyzer Model 224 allowed for stop-frame study of each frame for each segment of the film used in the study. Measurement techniques are outlined in Appendix C.

The output of the phototransducer for the glottal cycle was analyzed by measuring the deviation of the oscilloscope trace of the glottograph from the base line established by the 5k Hz signal. The drafting instruments developed and employed for this measurement procedure are described in Appendix C.

Amplitude and area curves were developed as a function of time and plotted for each experimental condition. Measurements were made on six complete cycles selected from the 50- to 60-foot portions on the 100-foot films. The curves developed through analysis of the data are presented in Appendix D.

Frequency of phonation was derived for each subject in each experimental condition by means of input from the Ampex tape recorder to the Honeywell model 1508A Visicorder. Wave-to-wave measurement of the output of each sample was made by measuring the wave from peak-to-peak and dividing this by the time interval selector of the Visicorder to obtain the period. Frequency in Hz was computed by the formula $F = 1/T$.

A summary table of frequency of phonation for each individual during each experimental condition may be seen in Appendix E.

The relative intensity levels were computed for each phonational sample. The output of the Ampex 352 dual channel, full-track tape recorder was coupled to a Bruel and Kjaer 2305 Graphic Level Recorder which recorded the sample signal at a mid-scale with a 50-dB potentiometer. The measures were made relative to this scale. These results are summarized in Table 6 in Appendix F.

To determine the relationship between the wave forms developed by measurement of the glottal area function derived through analysis of the photographic film and by measurement of the deviation of the quantity of light sensed by the photo-electric glottograph, the curves were normalized and a Pearson product-moment correlation coefficient was computed for each sample for each subject. In addition, confidence intervals were developed for each computation. To determine the degree of approximation to glottal area function produced by the data derived from the photo-electric glottograph within three registers, a comparison was also made between the correlation coefficients developed for the samples obtained from each subject.

CHAPTER III

RESULTS

The major purpose of this study was to determine whether photo-electric glottography was as valid for depicting glottal area function as frame-by frame analysis of ultra-high-speed film. The two investigative techniques were compared in three vocal registers (vocal fry, modal, and falsetto) produced by five normal larynges representing different ages and sexes (pre-adolescent male, adolescent male, post-adolescent male, adult male, and adult female). The raw data were acquired by recording glottal area vibrational variations simultaneously in high-speed motion pictures and in photo-electric glottogram oscillograph traces. The five subjects phonated the vowel /i/ at two fundamental frequency regions, one in each of two registers, modal and falsetto. In vocal fry registration, it was possible to obtain only two satisfactory samples of subjects phonating the vowel /i/ at appropriate fundamental frequencies. The reader should be aware of the difficulty of vocal fold exposure in this register (Timcke _et al_., 1959).

One sample of each experimental condition was obtained, the criterion measures were register production, vocal fold exposure, relative intensity, and phototransducer activity for each sample in each condition.

It should be noted that the glottal area function and the fundamental frequency of phonation obtained in the present study varied from subject to subject as well as from register to register. For example, Subjects One and Three were found to demonstrate incomplete glottal approximation in modal register, whereas, the other subjects did achieve complete vocal fold closure in this register. This manner of approximation in modal register is in disagreement with that found by other investigators (van den Berg, 1958, 1960; Vennard, 1960; Moore, 1968a). Further, the frequency of phonation in each of the registers differed from subject to subject. However, in each sample of register production the frequency produced by the individual subject was appropriate for the age and sex of that subject (Luchsinger and Arnold, 1965; Sedláčková, 1961; van Oordt and Drost, 1963). To identify the developmental stage and sex of each of the subjects, the following designations were used: Subject One, adult male; Subject Two, adult female; Subject Three, post-adolescent male; Subject Four, adolescent male; and Subject Five, pre-adolescent male.

Correlation of Glottal Area Function Depicted by Photo-electric Glottographs and Ultra-High-Speed Pictures

Modal register

The measurements of glottal area function derived from the frame-by-frame analysis were normalized for each of the subjects. These data were then compared to the normalized data derived simultaneously from the signal transmitted by the phototransducer of the photo-electric glottograph. The amplitude and area curves thus obtained for each of the five subjects producing modal register phonation are shown in Figures 3-7. These figures and Table 1 indicate that the phototransducer output and glottal area function measurements correlate significantly at the .05 level of confidence.

In view of the variability exhibited by the subjects during the production of the modal register frequencies, no definitive statement is possible about the ratio of the opening, closing, and closed phases of the vibratory cycle. It should be noted, however, that there appear to be several modes of vibration appropriate to this register.

Similarity of closure was noted between Subjects One and Three. Figures 3 and 4 clearly indicate that the frame-by-frame analysis and the glottogram show no complete closure for either of the two subjects. In addition, the two methods define the open quotient and speed quotient

f_o 210 Hz

Intensity 32 dB re 10 mV

Photographic ————————

Glottographic ----------

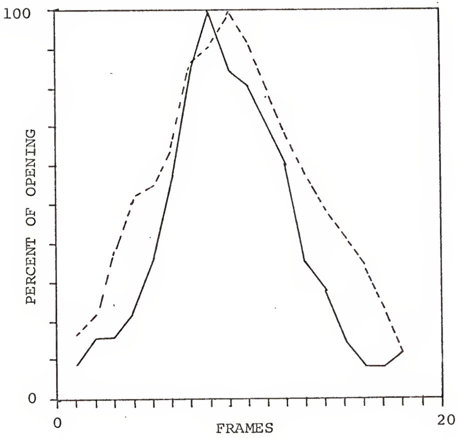

Figure 3. Plot of glottal area function and photo-electric glottograph for one normalized cycle. Subject 1, modal register.

equally well.[1] The vibratory cycle characteristic of Subject One began with a lateral movement of the upper margins of the vocal folds. Discernible opening began just anterior to the middle one-third of the vocal folds and proceeded toward the anterior and posterior commissures. As the upper margins completed their lateral displacements, the lower margins could be seen approaching the mid-line at the posterior one-third of the vocal folds. This closing movement proceeded synchronously to the anterior commissure. The upper margins began their adductory movement at the middle one-third and the closing gesture continued to the anterior commissure. As shown in Table 2, the open quotient was found to be .88, while the speed quotient was 1.0.

The opening phase noted in the vibratory cycle produced by Subject Three was found to show incomplete closure as indicated in Figure 4. Initial opening began at the posterior commissure. The phase relationship of the upper and lower margins of the vocal folds presented an appearance

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[1] Open Quotient will be defined by the formula:

$$\text{O.Q.}\ \frac{\text{Fraction of cycle during which glottis is open}}{\text{Duration of entire cycle}}$$

Speed Quotient will be defined by the formula:

$$\text{S.Q.}\ \frac{\text{Time of abduction or lateral excursion}}{\text{Time of adduction of medial excursion}}$$

(Timcke _et al_., 1959).

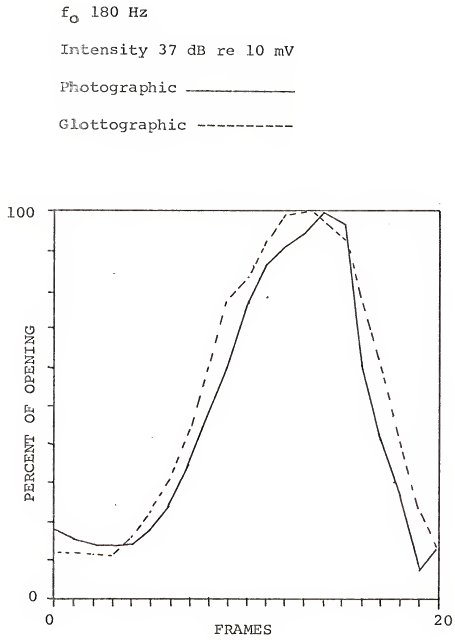

Figure 4. Plot of glottal area function and photo-electric glottograph for one normalized cycle. Subject 3, modal register.

similar to that of Subject One. During the opening phase, the only difference noted between the two was that the lower margins of the vocal folds were not visible. On closing, the upper margins appeared to move laterally while the lower lip of the vocal folds presented a synchronous closing movement originating at the posterior commissure. As this adductive movement was completed, the upper lip moved to the mid-line. During the closed phase, the mass of the thyroarytenoid muscles seemed to compress toward the mid-line. This movement continued into the beginning of the following opening gesture. A stiffening[2] of the edge of the vocal folds then appeared to occur. The open quotient was found to be .61 with a speed quotient of 2.0 as shown in Table 2. These figures were acquired through analysis of the averaged data derived by the two methods of investigation.

The vibratory pattern characteristic of Subject Two was found to employ a movement pattern more similar to that described by Timcke _et al_. (1958), in their discussion of the vocal fold margins. The opening commenced at the posterior commissure with the upper margins of the vocal folds separating first. This opening then seemed to progress to the middle one-third. The main body of the thyroarytenoid musculature appeared to move laterally away from the mid-line. Complete abduction to the anterior commissure was then achieved exposing the lower margins of the folds which seemed to be similar in contour but of smaller total area than that encompassed by the upper margins. This activity was followed by complete opening of the lower margins of the vocal folds. On closing, both vocal folds appeared to move synchronously toward the mid-line where they contacted each other simultaneously throughout their entire borders. During the closed phase, movement of the thyroarytenoid muscles toward the mid-line was observed. Figure 5 and Table 2 allow a definition of the open quotient to be .70, while the speed quotient may be calculated to be 1.75 as analyzed by an average of the two methods. The speed quotient suggests that the intensity of phonation was medium to loud (Timcke et al., 1958) which was confirmed by reference to the recorded sound.

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[2] Stiffening will be operationally defined as the appearance of a compact, dense, and fixed positioning of the vocalis musculature (van den Berg, 1958).

The action noted in the vibratory pattern for Subject Four was found to be grossly similar to that noted for Subject Two. This similarity may be noted by a comparison of Figures 5 and 6. Moreover, the stiffening posture of the

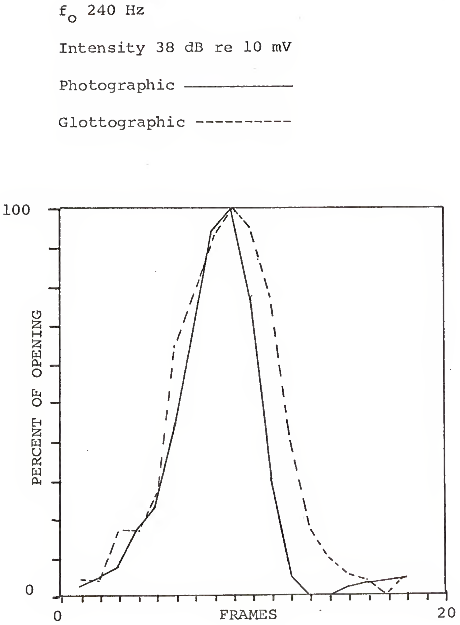

Figure 5. Plot of glottal area function and photo-electric glottograph for one normalized cycle. Subject 2, modal register.

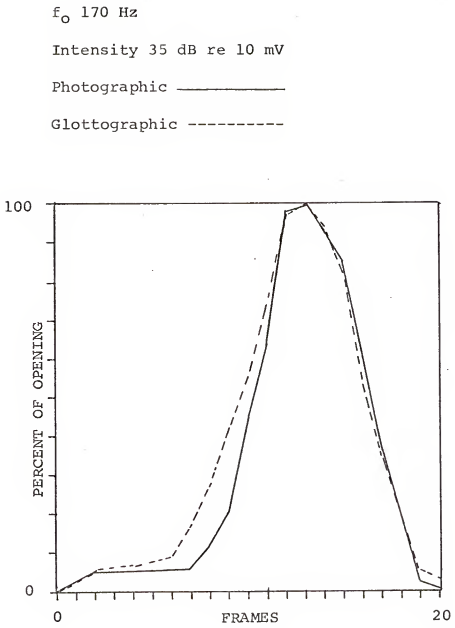

Figure 6. Plot of glottal area function and photo-electric glottograph for one normalized cycle. Subject 4, modal register.

vocal folds noted in the vibratory pattern of Subject Three was apparent during the opening phase for Subject Four. Of interest to the investigator was the initial opening gesture in which a massing of the upper margins of the vocal folds seemed to continue for several frames into the opening phase. However, as the closing phase began, the vertical expanse of the marginal surfaces of the vocal folds presented a somewhat concave appearance. Again, the initial adductory movement of the folds began at the posterior commissure. For this subject, analysis of the averaged data obtained from the phototransducer and the photographic film revealed the open quotient to be .57 with a speed quotient of 1.40 as shown in Figure 6 and Table 2.

The activity of the vocal folds of Subject Five differed somewhat from that of the other subjects. Specifically, during the closing gesture, the lower margins of the vocal folds approached initially at the posterior commissure. Although this gesture was not completed, the anterior portion of the folds did then adduct. Contrary to other observations made during the production of modal register, the upper margins of the folds began the adductory movement at the anterior commissure. Adduction was then characterized by symmetrical, progressive, medial movement of the vocal folds terminating in complete glottal closure. Some lateral movement of the thyroarytenoid muscle mass was noted. Figure 7 and Table 2 illustrate that the two methods of investigation indicated an open quotient of 1.0 with a speed quotient of 1.5 for this subject.

To determine the relationship between the two methods used in determining glottal area function, a Pearson product-moment correlation coefficient (Hays, 1963) and 95 percent confidence intervals (Walker and Lev, 1953) for each correlation were calculated. The results of this analysis are presented in Table 1. As may be seen from inspection of the table, the correlation between the photographic and glottographic methods for evaluating glottal area function in the modal register is significant.

Falsetto register

The results of analysis of the normalized amplitude and area curves derived through measurement of the glottal area function from the developed photographic film and the traces representing the deviations of the quantity of light sensed by the phototransducer for the five subjects producing phonational frequencies within their falsetto register range are shown in Figures 8-12. A significant correlation was found to exist between the results of the analysis obtained from the two methods of measurement.

f_o 360 Hz

Intensity 43 dB re 10 mV

Photographic ————————

Glottographic ----------

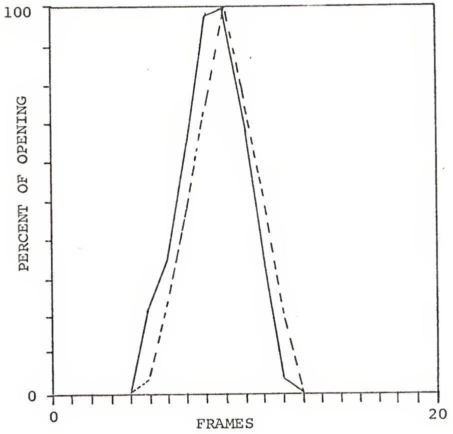

Figure 7. Plot of glottal area function and photo-electric glottograph for one normalized cycle. Subject 5, modal register.

Table 1. Summary table of correlation between photo-electric glottographic and photographic methods of analysis for modal register

			Confidence Intervals	
Subject	r	df	Lower Limit	Upper Limit
1	.90*	16	.747	.963
2	.92*	16	.795	.970
3	.97*	19	.926	.987
4	.98*	18	.949	.955
5	.96*	8	.836	.991

*Significant at the .05 level

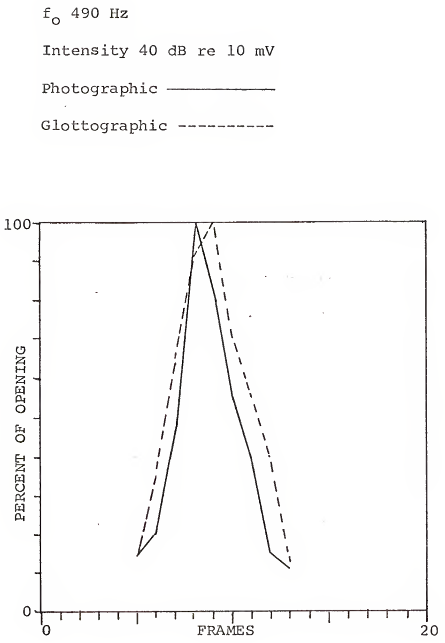

Figure 8. Plot of glottal area function and photo-electric glottograph for one normalized cycle. Subject 1, falsetto register.

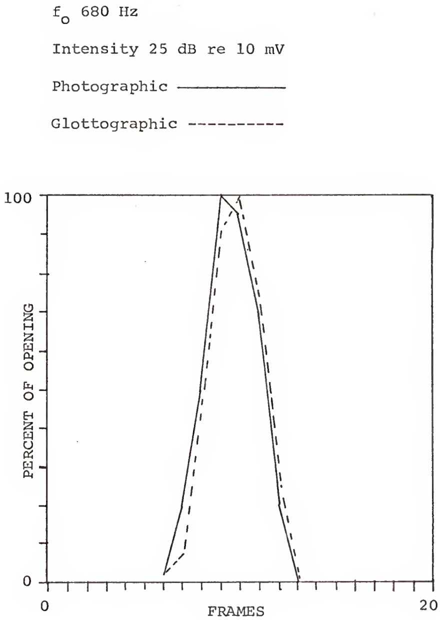

Figure 9. Plot of glottal area function and photo-electric glottograph for one normalized cycle. Subject 2, falsetto register.

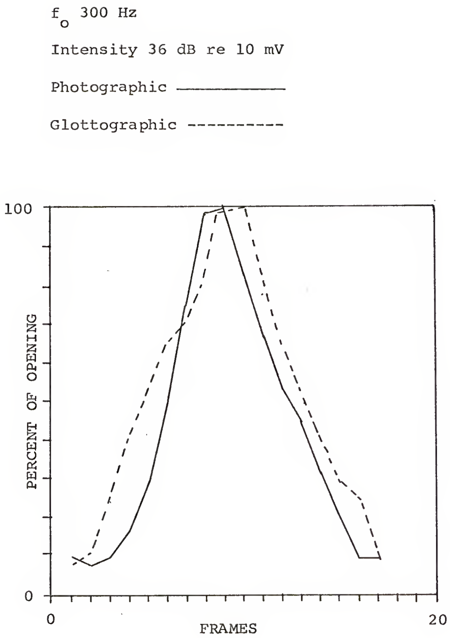

Figure 10. Plot of glottal area function and photo-electric glottograph for one normalized cycle. Subject 3, falsetto register.

f_o 580 Hz

Intensity 30 dB re 10 mV

Photographic ————————

Glottographic ----------

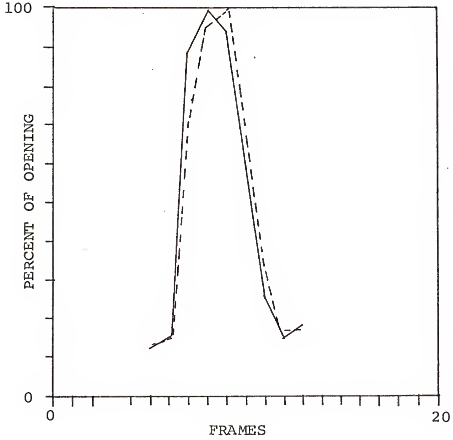

Figure 11. Plot of glottal area function and photo-electric glottograph for one normalized cycle. Subject 4, falsetto register.

f_o 760 Hz

Intensity 42 dB re 10 mV

Photographic ——————

Glottographic ----------

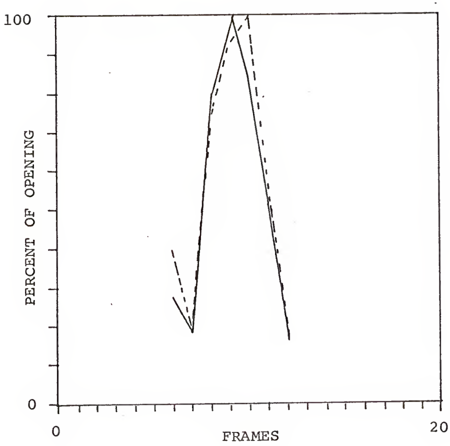

Figure 12. Plot of glottal area function and photo-electric glottograph for one normalized cycle. Subject 5, falsetto register.

There was great variability in the frequency of phonation produced by the subjects during the execution of this register. In addition, there appeared to be three modes of vibration exhibited by the subjects of this study.

Subjects One, Two, and Three seemed to present similar modes of vibration. There was no complete closure of the vocal folds during the "closed" phase. For these individuals, an opening at the posterior commissure was apparent. This is similar to the type of vibrational pattern described by Rubin and Hirt (1960) as open chink. For these subjects, opening was initiated at the middle one-third and was rapidly continued to the anterior commissure. On closing, the folds approached first at the anterior commissure and completed their closing gesture with contact of the middle one-third of the vocal folds. The figures associated with the glottal area function for each of the subjects reveal that the open quotient and the speed quotient were both found to be 1.0 (Table 2). This suggests that the intensity of production in this register was medium to high and that there was considerable tension of the vocal folds as predicted by Timcke _et al_. (1958) and Rubin and Hirt (1960).

The vibratory pattern for Subject Four differs from that previously described in the production of falsetto register in that, during the opening phase, the folds were seen to approximate at the middle one-third with an opening present at the anterior and posterior one-thirds of the vocal folds. Complete opening was then achieved with an apparent stiffening of the margins of the folds. Closure was accomplished in much the same manner as that of the aforementioned subjects. An inspection of Figure 11 and Table 2 reveals an open quotient of 1.0 with a speed quotient of .75.

A most unusual pattern of vibration was noted in the phonatory mechanism for Subject Five. Although no closed phase was accomplished, the opening first perceived was at the middle one-third of the vocal fold expanse rather than at the posterior portion as had been noted in the previous patterns. In addition, the opening phase showed an abduction of the anterior portion extending to the anterior commissure. On closing, the posterior one-third made adductory movements followed by adduction of the anterior portion of the vocal folds. Again, there appeared to be stiffening of the margins of the vocal folds. However, this process seemed to progress segmentally throughout the length of the vibrating vocal folds. It is evident from the results displayed in Figure 12 and Table 2 that the opening quotient for this subject was 1.0 with a speed quotient of .66.

A Pearson product-moment correlation coefficient and 95 percent confidence intervals for each correlation were calculated. The results depicted in Table 3 indicate that the correlation between the two methods of investigation is significant for the falsetto register. This finding is in agreement with the suggestion made by Köster and Smith (1970). The glottograms derived in falsetto register are more representative of glottal area function than in registers encompassing the lower phonational ranges.

Vocal fry register

For vocal fry register, the resulting normalized amplitude and area curves produced by two subjects are shown in Figures 13 and 14. Although the five subjects participating in the investigation were capable of producing vocal fry phonation, for only two of the subjects were measurable film images obtained. Analysis of the measurement of the glottal area function in the frame-by-frame display of the developed film and the deviation of the trace produced by the sensitivity of the phototransducer revealed that the correlation between the two methods of investigation is not as exact in vocal fry register as in the modal and falsetto

Table 2. Summary table of averaged indications of open quotient and speed quotient for each subject in modal and falsetto register phonation derived through analysis of photographic film and photo-electric glottograms*

	Modal Register		Falsetto Register	
Subject	O.Q.	S.Q.	O.Q.	S.Q.
1	.88	1.00	1.00	1.00
2	.70	1.75	1.00	1.00
3	.61	2.00	1.00	1.00
4	.57	1.40	1.00	.75
5	1.00	1.50	1.00	.66

*No figures for the open quotient or speed quotient for vocal fry phonation were included due to lack of protocols for this register.

Table 3. Summary table of correlation between photo-electric glottographic and photographic methods of analysis for falsetto register

			Confidence Intervals	
Subject	r	df	Lower Limit	Upper Limit
1	.95*	7	.775	.989
2	.98*	6	.889	.997
3	.94*	15	.838	.979
4	.98*	7	.905	.995
5	.97*	5	.807	.995

*Significant at the .05 level

f_o 10 Hz

Intensity 37 dB re 10 mV

Photographic ————————

Glottographic ----------

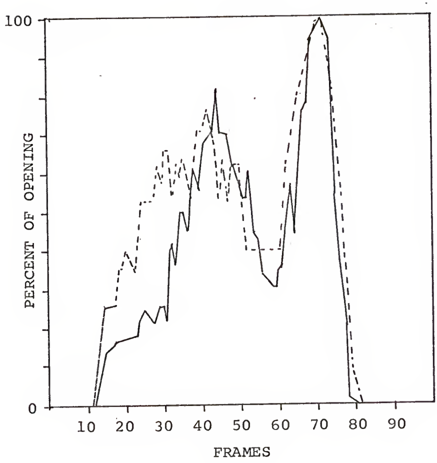

Figure 13. Plot of glottal area function and photo-electric glottograph for one normalized cycle. Subject 3, vocal fry register.

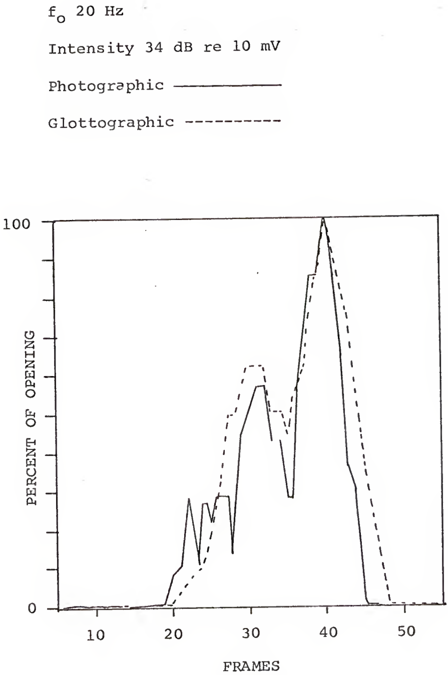

Figure 14. Plot of glottal area function and photo-electric glottograph for one normalized cycle. Subject 4, vocal fry register.

registers. However, it should be noted that a striking similarity exists between the derived curves.

The vibratory pattern displayed in Figure 13 in the production of vocal fry was regularly biphasic for Subject Three. Production of a multiphasic vibratory cycle is in agreement with the results of earlier investigations (Timcke et al., 1959; Moore and von Leden, 1958). The initial opening excursion was seen at the anterior commissure followed slowly by opening to the middle one-third of the vocal fold margin. There was an adductory motion leaving a narrow eliptical opening to the posterior commissure. This posture was maintained until the second excursion of the folds appeared. A lateral motion was visualized, followed by complete opening of the folds. Closing was characterized by a rapid closure of the anterior portion of the folds followed by complete anterior-posterior closure. The closed phase allowed for visualization of the participation of the ventricular folds. It should be noted that in no instance was the activity of the vocal folds obscured by the participation of the ventricular folds. As the margins of the folds closed, there appeared to be massing of the marginal area. The ventricular folds gradually receded into a completely abducted position. This observation is in agreement with the results reported in a recent laminagraphic investigation (Allen and Hollien, in press) which suggested that the ventricular folds operate in conjunction with the vocal folds in vocal fry phonation and, further, that the travelling wave from the true folds is continued into this mass.

The time ratio and area of the two opening gestures noted in the single vibratory cycle are of interest. The initial excursion occupied twice the time period noted for the second while the area measurement indicated an increase of 25 percent for the second excursion. The closed period accounted for approximately two-thirds of the entire period.

For Subject Four, the production of vocal fry registration was characterized by a vibratory cycle demonstrating a triple opening sequence and an occasional vibrational cycle presenting a single opening pattern. The initial excursion was evidenced by a small circular opening at the posterior commissure followed by a narrowing of this area. The second excursion demonstrated a triangular configuration; the smaller opening appearing at the posterior commissure. This opening was then modified to that of a narrow ellipse. The final abduction apparently involved a greater length of the folds and appeared to be symmetrically elliptical in shape. A rapid closure was then accomplished. The single opening pattern was seen only on occasion and may not have been representative of the subject's normal phonatory posturing in vocal fry phonation.

More participation of the ventricular folds was noted in the production of this register by Subject Four than by Subject Three. It should be noted also that for Subject Four, the vocal folds seemed to be covered by a considerable amount of mucus. The action of the ventricular folds was similar to that of Subject Three. Although protocols for defining the open quotient and speed quotient for a single cycle have not been established for vocal fry register, it is of interest to note the quotients for the excursions of the folds visualized in one vibratory cycle. In the photographic film analysis, Subject Four displayed an open quotient for the first excursion of 1.0 with a speed quotient of 3.43. The second excursion presented an open quotient of 1.0 with a speed quotient of 1.09; whereas the third abductory posture indicated an open quotient of 1.0 and a speed quotient of .60. The closed phase for the entire cycle occupied about one-third of the entire cycle.

The results of computation of a Pearson-r between the two methods of investigation, together with 95 percent confidence intervals for each correlation, are shown in Table 4. Indications are that, although correlation does

Table 4. Summary table of correlation between photo-electric glottographic and photographic methods of analysis for vocal fry register

			Confidence Intervals	
Subject	r	df	Lower Limit	Upper Limit
3	.65*	128	.153	.943
4	.84*	78	.761	.895

*Significant at the .05 level

exist, the phototransducer is not capable of sensing the same information as that derived visually from photographic film.

For the five subjects used in the present investigation, it may be concluded that the photo-electric glottograph is as valid a method for depicting glottal area function as a frame-by-frame analysis of ultra-high-speed film in the modal and falsetto registers. In addition, although the correlation found between the two methods of investigation is not as high in the vocal fry register, the photo-electric glottograph does appear to be capable of generating reasonably approximate information.

CHAPTER IV

DISCUSSION

The subjects in the present investigation utilized essentially normal laryngeal mechanisms (as determined by the subject selection criteria) to produce samples of vocal fry, modal, and falsetto phonation which were analyzed through measurements obtained from a light sensing device and a high-speed camera. The results indicate that the two methods of analysis are highly correlated in their ability to depict similarly shaped area and amplitude curves for the modal and falsetto registers. In addition, although the statistical analysis of the correlation between the curves developed by the two methods in vocal fry phonation did not indicate a one-to-one relation, there was striking similarity in the overall configuration.

Glottographic Response and Vibratory Pattern in Modal Register

Prior to this study, few studies had been made employing simultaneous recordings of vocal fold activity through the utilization of glottography and photography. Moreover, the investigators who did obtain such simultaneous recordings (Coleman and Wendahl, 1967, 1968) found that the photoglottograph was limited in providing accurate indications of glottal area function. The present study disagrees with those findings in the modal register. Although it was apparent that the phototransducer signaled the opening phase earlier than the occurrence of this phase became visible, this is not in disagreement with the suggestion of Sonesson (1960). He surmised that the glottograph could be useful in defining the phase relationship of the lower and upper edges of the vocal folds. It is possible that such complex glottal configurations can cause the differences noted in the results of this study. Timcke et al. (1958) found that, although the shape of the amplitude curves produced by the upper and lower margins of the vocal folds was similar, there was a definite phase shift between the two movements. The upper margin was seen to lag behind the lower margin in the closing phase of the vibratory cycle. This finding would seem to be verified by the results of this study.

Variations in the vibratory patterns produced by the subjects of this study suggest that in the modal register there is no completely predictable mode of vibration. Brackett (1947) found not only differences between subjects but also intra-individual differences. A careful comparison of individual vocal fold movement and vocal intensity confirmed the hypothesis set forth by van den Berg _et al_. (1957) that the Bernoulli effect, i.e., the negative pressure in the glottal air, is enhanced with an increase in tone intensity and air flow thereby drawing the vocal folds more forcibly toward each other.

Observations also supported the myoelastic-aerodynamic theory of phonation. The vocal fold margins of two of the subjects participating in the study demonstrated an active longitudinal tensing. van den Berg (1968a) reports that this contraction is expected in sustained phonation of a given fundamental frequency. The concave appearance of the vocal fold margins visualized in the phonation of one subject suggests an active participation of the vocal muscles.

Glottographic Response and Vibratory Pattern in Falsetto Register

The correlation between the measurements of glottal area produced by photo-electric glottographs and by the photographic film in falsetto register found in this study tend to conform to the conclusions stated by Köster and Smith (1970). They found that in phonations in the higher frequencies the glottograph provided a more accurate representation of glottal area function than in the lower frequencies. The present results indicate that the glottographs are significantly related to glottal area function in the falsetto register. It may be surmised that the thin shape of the glottal margins creates single, relatively simple glottal folds in which there is no change of phase relationship between an upper and lower margin. Thus, it could be expected that the light passing between the vocal folds would not be impeded by vocal fold tissue during the opening and closing phases of the vibratory cycle.

Although Rubin and Hirt (1960) indicated three basic patterns of vibratory activity in the falsetto, only that designated as open chink was observed in this investigation. However, two subjects presented vibratory patterns that have not previously been described.

A narrow opening at the posterior and anterior commissures with closure at the middle one-third of the vocal fold expanse characterized the vibratory pattern for one of the subjects. Contrary to this mode of vibration, another of the subjects achieved closure that may be described as "tight" at the posterior and anterior commissure. The opening thus accomplished only encompassed the middle one-third of the vocal folds.

In all cases, the appearance of the vocal folds did correspond with that suggested by other investigators (van den Berg, 1960; Luchsinger and Arnold, 1965). The vocal folds were indeed elongated and appeared to be thin in mass. There also seemed to be an obvious stiffening of the vocal fold margins which suggests a longitudinal tension in the vocal ligaments without an active vibratory participation of the vocal muscles. However, the visualization of adduction of the middle one-third of the vocal folds suggests that myoelastic properties may have been active in at least this individual's production of falsetto register. The appearance of tight closure of the anterior and posterior commissures with resulting open chink at the middle one-third may possibly be explained by myoelastic properties. It was obvious that aerodynamic properties were predominant in the falsetto production of the remaining subjects.

Glottographic Response and Vibratory Pattern in Vocal Fry Register

Previous investigators of the vibratory pattern for vocal fry phonation have obtained photographic film of phonation that should be considered as high fry or fry mixed with modal (Timcke et al., 1959; Moore and von Leden, 1958). The samples obtained in this investigation were of fundamental frequencies more appropriate to this register (Allen and Hollien, in press; Hollien et al., 1966; Hollien and Michel, 1968; Hollien et al., 1969). Although the results for this register are based on the production of only two subjects, it was concluded that this information was valid. The magnitude of the correlations indicated inexact replication of vocal fold activity by the photoelectric glottograph as compared with the analysis of photographic film. However, the curves representing the variations of quantity of light and the glottal area function do seem to bear a striking similarity.

Information on the physiologic parameters of vocal fry phonation have not been completed. However, the glottograms resulting from this study resemble those analyzed by Ohala (1966) and Fourcin and Abberton (1971). These investigators termed the vocal production as creaky voice.

The vibratory pattern exhibited by one of the subjects was like that defined by Moore and von Leden (1958) as dicrotic dysphonia. The biphasic excursions of the vocal folds were found to represent amplitudes similar to those suggested by those investigators, i.e., the first was approximately 25 percent smaller in amplitude than the second.

The vibratory pattern characteristic of the fourth subject was unusual in that it appeared to represent three definite excursions of the vocal folds. Each of the excursions seemed to be about 25 percent larger than the preceding one. It has been suggested (Hollien et al., 1966) that there may exist various modes of vibration for this register.

Hollien (1971) has postulated that myoelastic properties are predominant in vocal fry register. Visualization of the laryngeal mechanism reveals that this must indeed be the case. However, due to the complexity of relationships of the structures involved in the production of this register, much more extensive investigation of the vocal phenomenon is indicated before aerodynamic properties can be dismissed as contributory to the control of change of frequency.

CHAPTER V

SUMMARY AND CONCLUSIONS

The purpose of this investigation was to determine the validity of the information concerning vocal fold activity derived through measuring the quantity of light passing through the glottis by comparing these data with measurements of glottal area taken from the photographic images. A second purpose was to describe and compare the characteristic glottal configurations in falsetto, modal, and vocal fry registers of pre-adolescent, adolescent, post-adolescent, and adult subjects as revealed by the two methods of measuring glottal area function. Based on the hypothesis that measurement of the quantity of light passing through the glottal area should reveal the same information as that derived from measurement of the discernible space between the vocal folds, simultaneous recordings on photographic film were obtained of the image of the vocal folds, the voice signal, and the deviations sensed by the phototransducer during vocal fry, modal, and falsetto phonation. Recordings were made during sustained phonation of the vowel

/i/ at frequencies appropriate to the vocal fry, modal, and falsetto registers. Deviations of the quantity of light were sensed by a phototransducer attached to the space between the thyroid and cricoid cartilages. The fundamental frequency and intensity of phonation were recorded on magnetic tape from the acoustic signal input to a probe tube microphone inserted into the oral cavity of the subject. The visual image of the vocal fold activity was photographed from the fixed laryngeal mirror introduced into the pharynx. The voice signal, deviations of the light quantity and a 5k Hz monitoring signal were displayed on the face of an oscilloscope and photographed simultaneously with the mirrored laryngeal activity by an ultra-high-speed camera. The voice signal recorded on the tape recorder was subsequently submitted to fundamental frequency and intensity analysis. Glottal area measurements were made from the photographic film by polar planimeter methods and by measuring the deviations of the light quantity. The data were normalized and submitted to statistical analysis in order to determine the correlation between the glottal area curves depicted by the photo-electric glottograph and the frame-by-frame analysis of the visual image in each of three registers.

From the investigation the following findings were obtained:

1. The measurements of the light deviations sensed by the photo-electric glottograph during laryngeal vibrations correlate significantly at the .05 level of significance with the photographic film frame-by-frame measurements of the visual image in modal and falsetto register.
2. The glottograms resulting from measurement of vocal fry phonation approximate those derived from photographic film measurement, however the correlation between the two curves is not as high in this register as is the case in modal and falsetto registers.
3. Inter-individual and intra-individual differences of vibratory patterns of phonation were found in vocal fry phonation.
4. During modal range phonation, there appeared to be no established vibratory pattern for all subjects.
5. Aerodynamic properties may not completely account for the vocal fold activity observed in the subjects of this study in the production of falsetto register.

It appears, therefore, that the photo-electric glottograph is a valid method of determining glottal area function. This conclusion, which is also supported by data obtained using a photo-electric glottograph and separate photographic film (Sonesson, 1960), may result in more complete understanding of the complex relationship of the upper and lower margins of the vocal folds. It might also result in a correlation between acoustically and physiologically derived data, i.e., through an inverse filtering process it may be possible to separate from the acoustically derived data valid information about the glottal area function.

The presence of at least two examples of variations from the vibratory pattern expected in falsetto register suggests a need for collecting a large and representative sample for obtaining normal values of the vibratory pattern of the vocal folds. In addition, the contribution of myoelastic properties should be examined in this register.

The subjects participating in this investigation represented a wide age differential and it was found to be possible to obtain laryngeal photographs of the pre-adolescent, adolescent, and post-adolescent aged individuals without undue difficulty. Therefore, this suggests that photographic investigation of the phonatory mechanism at different stages of maturation may result in more adequate understanding of the phenomenon of voice change.

APPENDICES

APPENDIX A

PHOTOGRAPHIC SEQUENCE

Photographic Sequence Followed Throughout the Experiment

Phototransducer attached to space between thyroid and cricoid cartilages.

1. Vocal fry register /i/
2. Millimeter grid photographed as the phototransducer transmits a "no response" signal to the oscilloscope.
3. Modal register /i/
4. Millimeter grid photographed as the phototransducer transmits a "no response" signal to the oscilloscope.
5. Falsetto register /i/
6. Millimeter grid photographed as the phototransducer transmits a "no response" signal to the oscilloscope.

APPENDIX B

FORM USED IN THE JUDGMENT OF SUBJECT PRODUCTION OF FALSETTO REGISTER

JUDGMENT FORM USED BY PHONETICIANS

Please indicate with a check mark (X), if you judge this sample of phonation to be within the subject's falsetto range.

Subject	Yes	No
1	____	____
2	____	____
3	____	____
4	____	____
5	____	____

APPENDIX C

PROCEDURE FOR MEASURING GLOTTAL AREA FUNCTION

PROCEDURES FOR MEASURING GLOTTAL AREA FUNCTION

A. Photographic film image. The Kodak Photo-Optical Data Analyzer and an auxiliary viewing system were utilized in the detailed study of glottal area function for each subject in each experimental condition. After the film image passed through the lens system, it was reflected upward by a mirror placed at a 70 degree angle to a second mirror placed above the main body of the analyzer at a 15 degree angle. This mirror, in turn, redirected the image downward to a layout pad situated 66 inches from the mirror. The linear enlargement ratio of the picture on the film to the projected image was 1:27. The area of the vocal fold opening was traced onto the layout pad and glottal area function of the vocal folds was determined by traditional polar planimeter methods. The space between the vocal folds was outlined by the tracer point of the Keuffel and Esser model 620005 Compensating Polar Planimeter for each frame. A fine line was drawn across the periphery of the glottal area to mark the starting and finishing point. The tracer point was placed precisely at the beginning line and the scale set to zero. The outline of the opening was then circumscribed to the starting point and a reading made. Second and third circuits of the area were made with a measurement reading being made at the end of each circuit. These three readings were then averaged to obtain area measurement in square centimeters.

B. Glottographic images. Immediately following the tracing of the glottal area, the frame displaying the glottographic signal corresponding to the first measured frame of the photographic film was determined. The signal from the electro larynx and the signal from the flash/sync generator allowed for identification of corresponding frames. The lines produced by the input of the phototransducer to the oscilloscope were measured from the parallel 5k Hz lines at a constant position for each photographic film frame. A straight line was scribed on a layout pad and placed under the image of the 5k Hz line and used as a base line. This line also served as an aid in the alignment of the parallel guide instruments employed in drafting the deviations produced by the glottograph and the voice traces. The position for measuring was chosen for consistent clearness throughout the series and held constant. A diagram of the measuring devices used in the data reduction for this investigation may be seen in Figure 15.

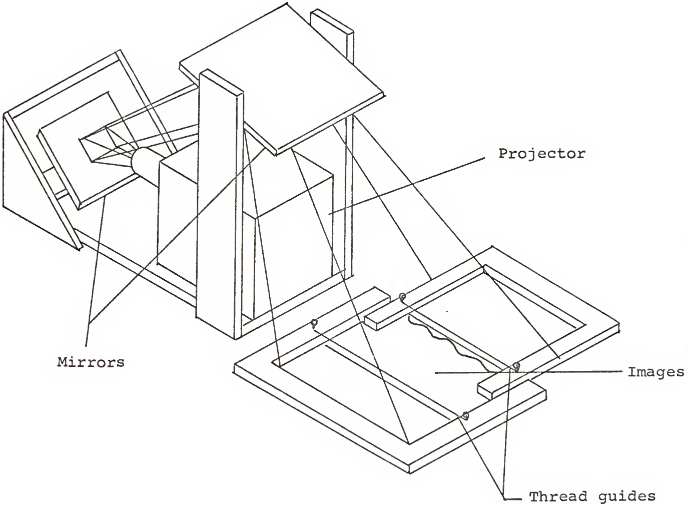

Figure 15. Diagram illustrating the measurement procedures used in data reduction for the analysis of glottal area function

APPENDIX D

AMPLITUDE AND AREA CURVES DERIVED THROUGH GLOTTOGRAPHIC AND PHOTOGRAPHIC FRAME-BY-FRAME ANALYSIS

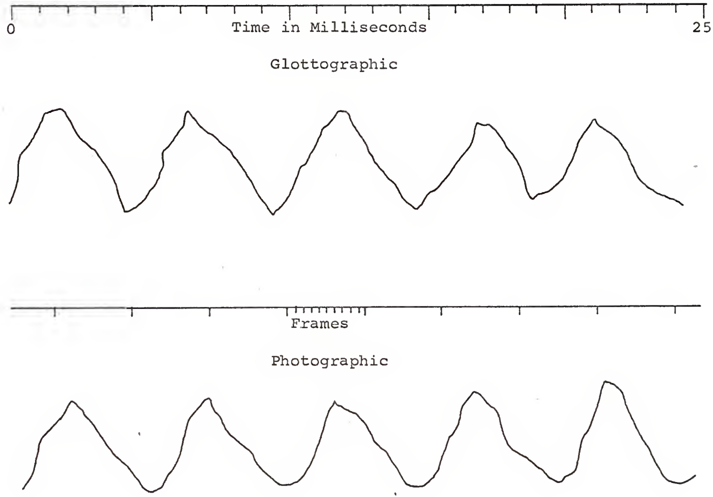

Figure 16. Comparison of photo-glottographic and photographic frame-by-frame analysis for the vowel /i/ produced in modal register for Subject 1

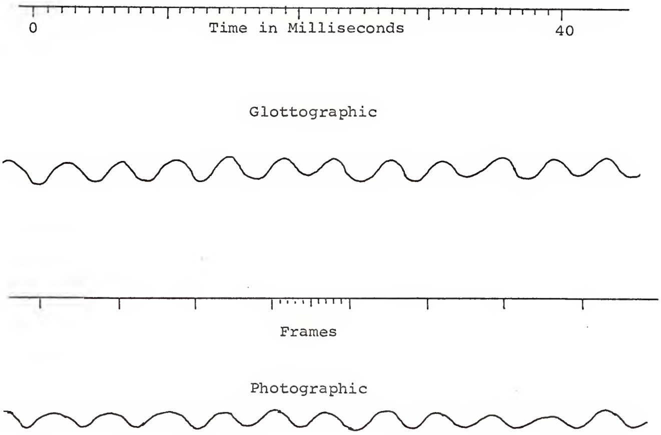

Figure 17. Comparison of photo-glottographic and photographic frame-by-frame analysis for the vowel /i/ produced in modal register for Subject 2

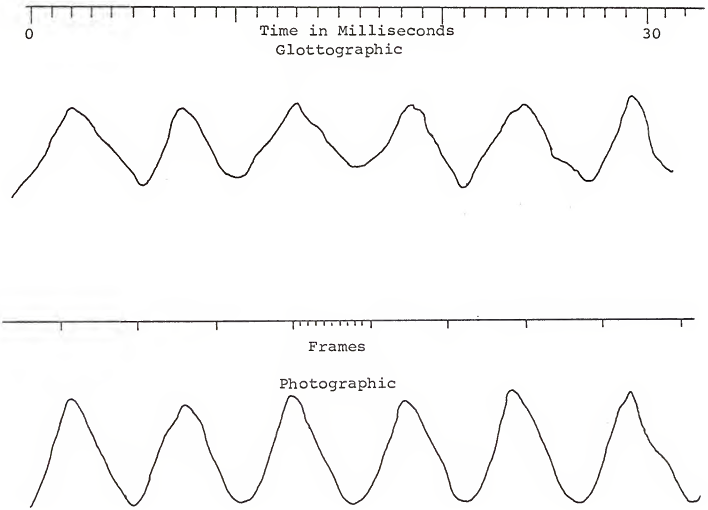

Figure 18. Comparison of photo-glottographic and photographic frame-by-frame analysis for the vowel /i/ produced in modal register for Subject 3

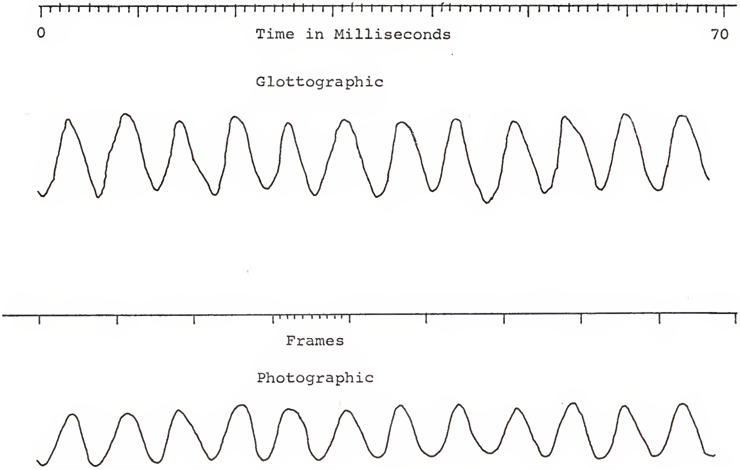

Figure 19. Comparison of photo-glottographic and photographic frame-by-frame analysis for the vowel /i/ produced in modal register for Subject 4

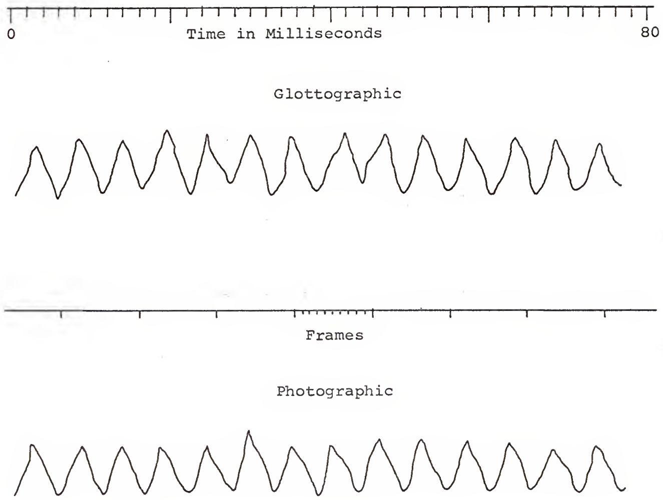

Figure 20. Comparison of photo-glottographic and photographic frame-by-frame analysis for the vowel /i/ produced in modal register for Subject 5

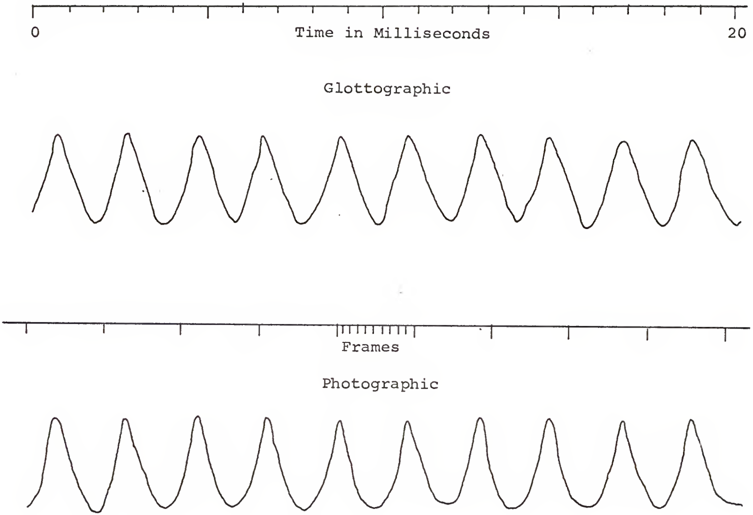

Figure 21. Comparison of photo-glottographic and photographic frame-by-frame analysis for the vowel /i/ produced in falsetto register for Subject 1

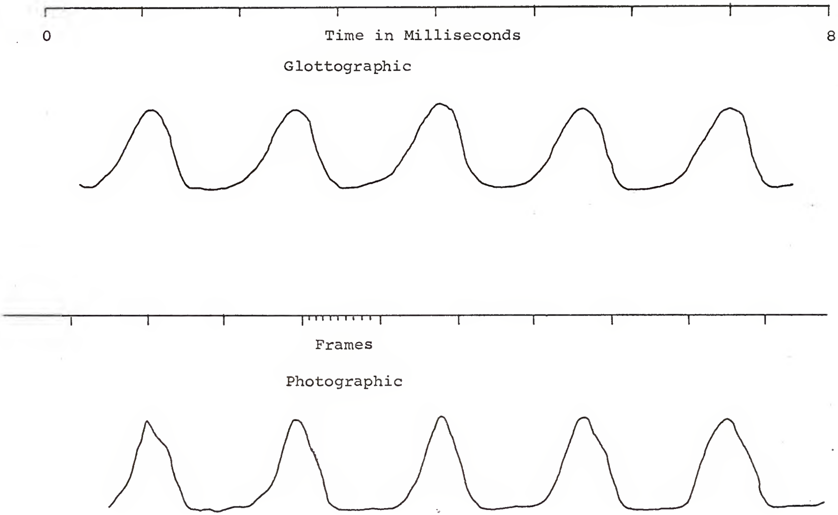

Figure 22. Comparison of photo-glottographic and photographic frame-by-frame analysis for the vowel /i/ produced in falsetto register for Subject 2

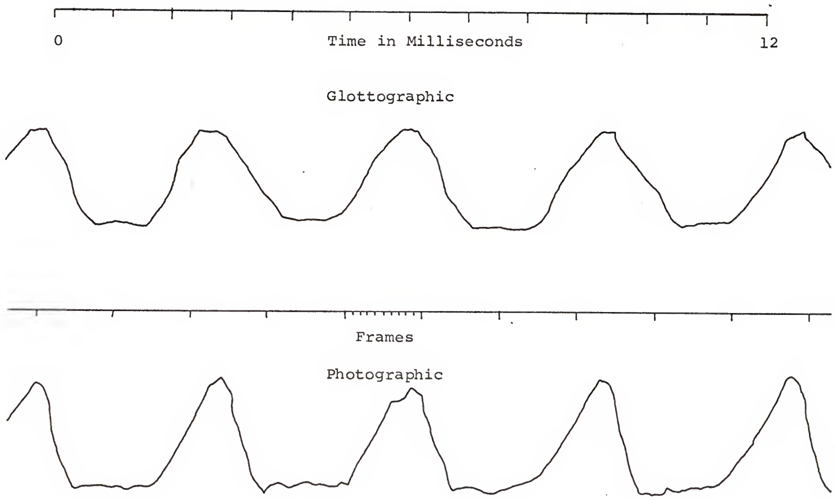

Figure 23. Comparison of photo-glottographic and photographic frame-by-frame analysis for the vowel /i/ produced in falsetto register for Subject 3

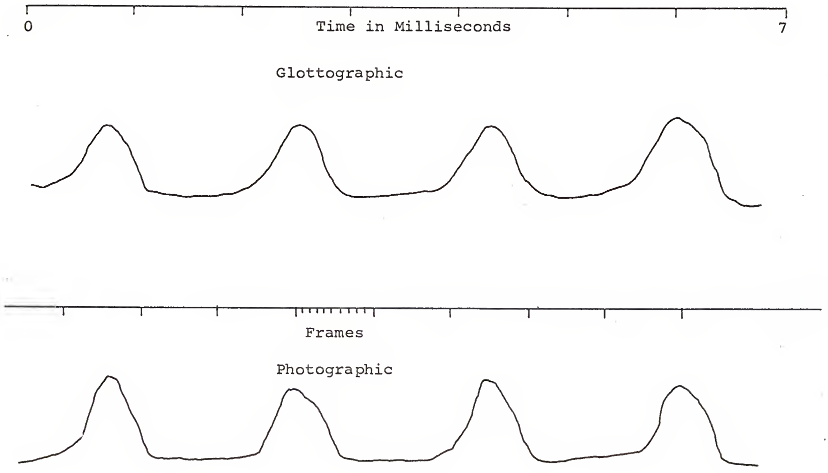

Figure 24. Comparison of photo-glottographic and photographic frame-by-frame analysis for the vowel /i/ produced in falsetto register for Subject 4

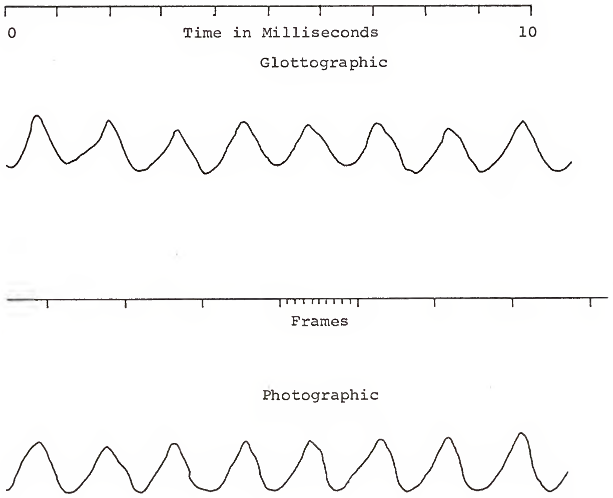

Figure 25. Comparison of photo-glottographic and photographic frame-by-frame analysis for the vowel /i/ produced in falsetto register for Subject 5

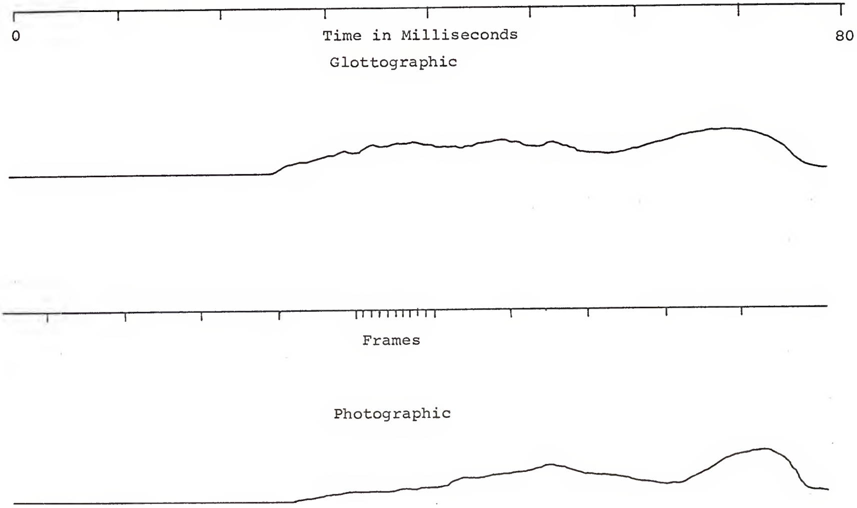

Figure 26. Comparison of photo-glottographic and photographic frame-by-frame analysis for the vowel /i/ produced in vocal fry register for Subject 3

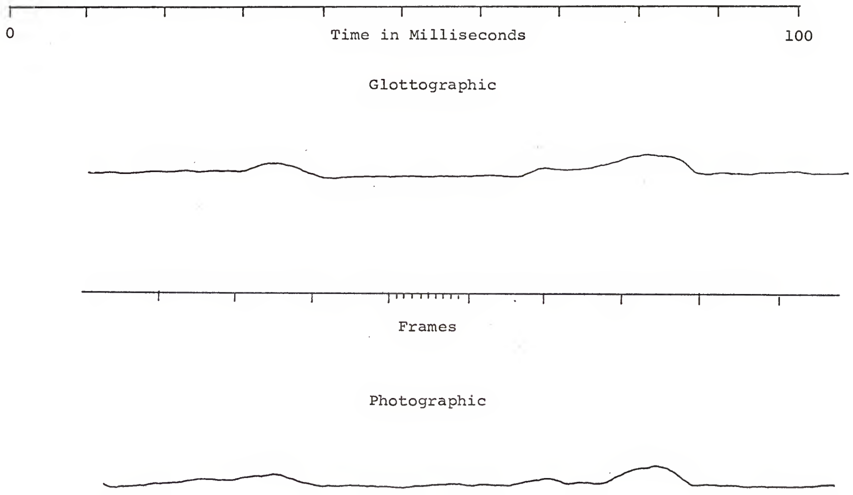

Figure 27. Comparison of photo-glottographic and photographic frame-by-frame analysis for the vowel /i/ produced in vocal fry register for Subject 4

APPENDIX E

FUNDAMENTAL FREQUENCIES

Table 5. Fundamental frequencies produced by five subjects used in the present investigation. The measures are reported in Hz for the sustained vowel /i/ produced in vocal fry, modal, and falsetto registers.

Subject	Vocal Fry	Modal	Falsetto
1	30*	210	490
2	10*	240	680
3	10	180	300
4	20	170	580
5	20*	360	760

*It should be noted that although these subjects were capable of producing phonation within vocal fry register, intrusive movement of the epiglottis prevented exposure of the vocal folds and consequent measurable photographic film. Of considerable interest, however, are the data derived by means of the phototransducer which seem to indicate that glottal area was defined by change of light quantity penetrating the area between the vocal folds.

APPENDIX F

RELATIVE INTENSITY

Table 6. Relative intensity levels of phonation for the five subjects used in the present investigation. The measures are reported in dB for the vocal fry, modal, and falsetto registers

Subject	Vocal Fry	Modal	Falsetto
1	15	32	40
2	38	38	25
3	37	37	36
4	34	35	30
5	30	43	42

Note: The computational formula used in obtaining these relative intensity levels may be described by this formula: value in dB from the recording plus the dB value indicated by the input potentiometer-re 10 mV.

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BIOGRAPHICAL SKETCH

R. Joyce Redus Harden was born June 27, 1929, at McCaulley, Texas. In June, 1945, she was graduated from Hamlin High School, Hamlin, Texas. She received a Bachelor of Arts degree with a major in Speech in June, 1949, from Texas Technological College, Lubbock, Texas. She taught in the Brown Schools in Austin, Texas, as a teacher of Exceptional Children in 1950. In 1953 she was employed as a classroom teacher of the deaf in the public schools of Fort Worth, Texas. She taught at the Ridglea Presbyterian Day School, Fort Worth, Texas, as a kindergarten teacher in 1964. In June, 1965, she enrolled in the Graduate School of Texas Christian University where she was granted a teaching assistantship. In August, 1967, she was graduated from Texas Christian University with a Master of Arts degree with a major in Speech Pathology. She was appointed to the faculty as an Instructor in 1967. In 1970, she was granted a leave of absence from Texas Christian University and enrolled in the Graduate School of the University of Florida in September of that year.

She held an assistantship there until September, 1971, followed by a teaching associate appointment until June, 1972.

She is a member of Alpha Psi Omega, Sigma Alpha Eta, the Texas Speech and Hearing Association, and The American Speech and Hearing Association. She holds professional certification in speech and hearing therapy in the state of Texas, and the Certificate of Clinical Competence in Speech Pathology in the American Speech and Hearing Association.

She is married to Robert Wayne Harden and is the mother of three sons.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

G. Paul Moore

G. Paul Moore, Chairman
Professor of Speech

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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This dissertation was submitted to the Department of Speech in the College of Arts and Sciences and to the Graduate Council, and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

June, 1972

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